

Further Investigations of a Variation of Geomagnetic Activity with Lunar Phase

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Abstract. The previously studied variation of geomagnetic activity with lunar phase indicates a general decrease in geomagnetic activity of about 4% for several days before full moon and an increase of about 4% for several days after full moon. Substantial evidence is presented indicating that the observed variation of geomagnetic activity with lunar phase requires lunar latitudes at full moon within about 4° from the ecliptic plane. It is demonstrated that the influence of a variable lunar parallax must be extremely small, if it exists at all. Some difficulties are presented with both a tidal mechanism and a geomagnetic tail-neutral sheet mechanism for explaining the observed variation of geomagnetic activity.

Introduction. Based on an analysis of 31 years of K_p data, a variation of geomagnetic activity with lunar phase has recently been indicated by *Bell and Defouw* [1964] and *Stolov and Cameron* [1964]. They find a decrease of geomagnetic disturbance for several days before full moon and an increase of geomagnetic disturbance for several days after full moon. The statistical significance of the results is well established. The earlier work of *Bigg* [1963a, b] claimed a decrease of geomagnetic activity at new moon.

Davidson and Martyn [1964] and *Michel et al.* [1964] were unable to find any dependence of geomagnetic activity on lunar phase. The former group applied the conventional harmonic dial method of variance analysis to 30 years of A_p data and failed to detect any evidence of a lunar effect. The inability of this technique to detect a lunar influence is not surprising when one notices the similar amplitudes of the *Stolov and Cameron* [1964] random-data Figures 2 and 3 and their lunar-phase Figure 1. *Michel et al.* did not find a lunar effect in the autocorrelation function based on merely 14.3 months of K_p data. They did not evaluate statistically the run of below-average values of geomagnetic activity before full moon or the run of above-average values of geomag-

netic activity after full moon shown in their analysis of 30 years of K_p data. A more comprehensive power spectrum analysis of 80 years of C_p data by *Shapiro and Ward* (private communication, 1965; to be published) gives evidence of a 29.5 days peak in the spectrum.

There is little to be gained by subtle ad hominem arguments or by sterile statistical significance tests without physical understanding. Further investigations are undertaken herein of the variation of geomagnetic activity with lunar phase to help in discovering the factors most influential in creating the variations about full moon. Substantial evidence is presented

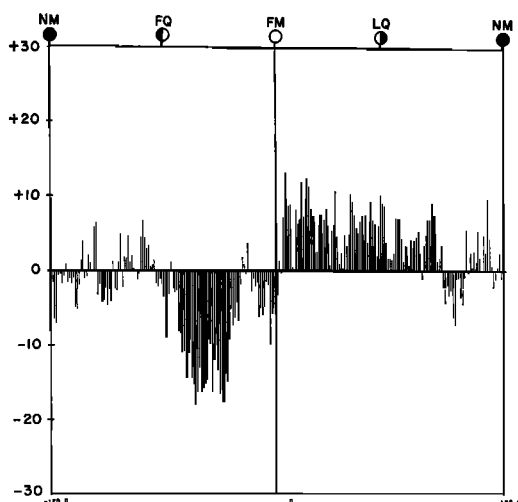


Fig. 1. Mean values of the per cent departures of K_p as a function of lunar phase (half data with lunar latitude at full moon less than 3.5°).

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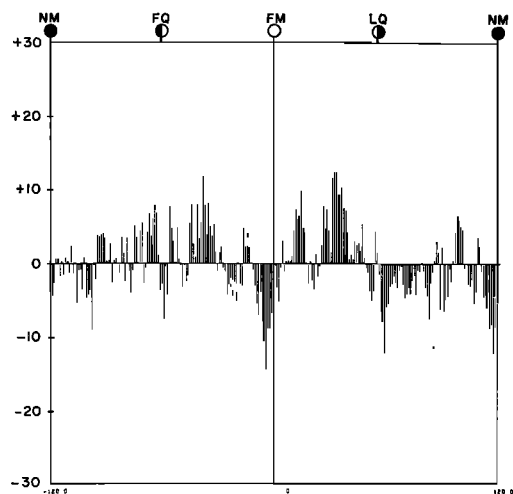


Fig. 2. Same as Figure 1 (half data with lunar latitude at full moon greater than 3.5°).

indicating a clear geomagnetic activity-lunar phase relationship for cases where the lunar latitude at full moon is less than about 4° . No effect is evident at larger angles from the ecliptic plane. The influence of a variable lunar parallax at full moon is not nearly so certain.

1. *Lunar latitude at full moon.* (a) The angular distance of the moon from the plane of the ecliptic at full moon varies from approximately 0° to $\pm 5^\circ$. About half of the 383 lunar periods for the years 1932–1962 fall within 3.5°

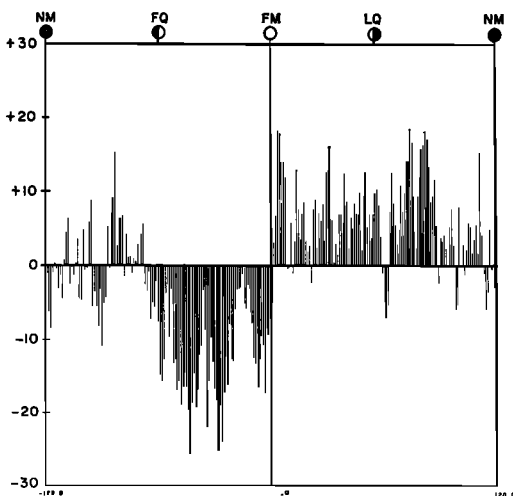


Fig. 3. Same as Figure 1 (quarter data with small \bar{K}_p and lunar latitude at full moon less than 3.5°).

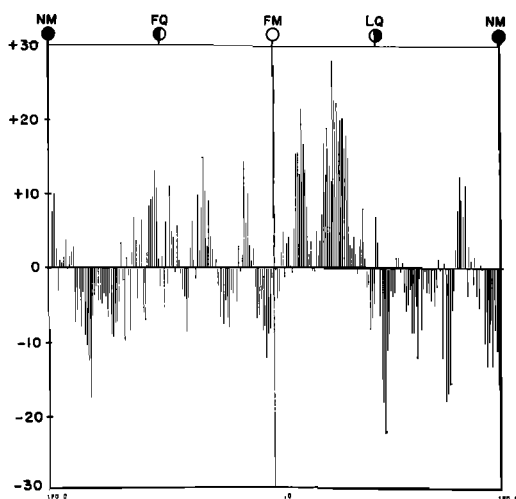


Fig. 4. Same as Figure 1 (quarter data with small \bar{K}_p and lunar latitude at full moon greater than 3.5°).

of the ecliptic plane. Using the superposed epoch method described by *Stolov and Cameron* [1964], the per cent departure analysis of the K_p data for this close-to-plane half is shown in Figure 1. The far-from-plane half is shown in Figure 2. The variation of geomagnetic activity with lunar phase, discussed previously, is clearly present in Figure 1. The resemblance of Figure 2 to the random-data cases is equally striking.

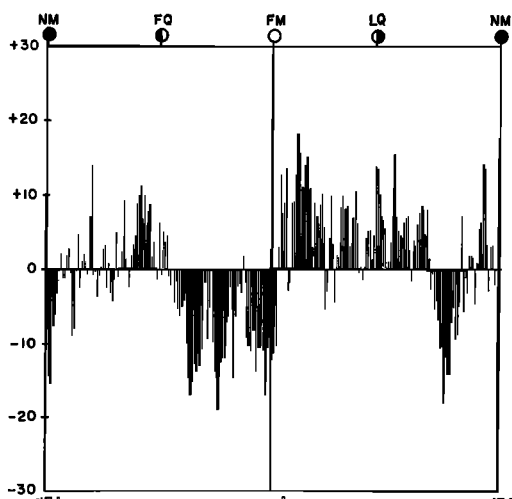


Fig. 5. Same as Figure 1 (quarter data with lunar latitude at full moon between 2° and 3.5°).

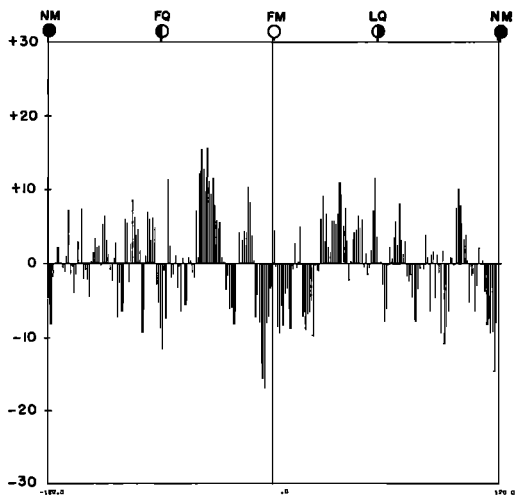


Fig. 6. Same as Figure 1 (quarter data with lunar latitude at full moon between 4.5° and 5°).

(b) Since a lunar effect is not evident during disturbed times [Stolov and Cameron, 1964; and Bartels, 1964], the 383 lunar periods are ranked according to their \bar{K}_p (average value for the lunar month) and are then separated into two groups. The 192 lunar periods of small \bar{K}_p are again divided into two groups on the basis of lunar latitude. The per cent departure analysis is then applied to the 96 cases of small \bar{K}_p in which the angle with the ecliptic plane is less than 3.5°; it is shown in Figure 3. The 96 cases of small \bar{K}_p and angle greater than 3.5° are shown in Figure 4. Here once again the close-to-plane group shows the lunar effect clearly present, and the far-from-plane group is essentially random.

(c) A critical lunar latitude search was undertaken by dividing the 383 lunar periods into four equal groups on the basis of lunar latitude. The first group (not shown) from approximately 0° to 2° shows the lunar effect distinctly. Figure 5 for the second group from approximately 2° to 3.5° shows the lunar effect clearly evident. The third group (not shown) from approximately 3.5° to 4.5° represents a gradation between Figures 5 and 6. Figure 6 for the last group from approximately 4.5° to 5° is definitely random. A physical mechanism to account for the variation of geomagnetic activity with lunar phase must explain the disappearance of the effect for full moons above about 4°.

(d) The probabilities of chance occurrence

TABLE 1. Probability of Chance Occurrence for Lunar Latitude Studies

Lunar Latitude Studies	Excursion Length Method	Excursion Area Method
Fig. 1	≈ 0.000	≈ 0.000
Fig. 2	0.566	0.799
Fig. 3	≈ 0.000	≈ 0.000
Fig. 4	0.740	0.198
Fig. 5	0.107	0.096
Fig. 6	≈ 1.000	≈ 1.000

of the results presented above, determined both by the method of excursion length and by the method of excursion area discussed in detail by Stolov and Cameron [1964], are here adjusted to the appropriate sample length being studied. The probabilities, listed in Table 1, are seen to be essentially zero in Figures 1 and 3 and near the traditional 5% level of statistical significance in Figure 5. The random nature of Figures 2, 4, and 6 is also confirmed.

(e) As a further confirmation of the latitude effect, the 191 lunar epochs representing the large \bar{K}_p half of the data are divided into a close-to-plane quartile and a far-from-plane quartile and subjected to the same per cent departure and probability analysis (figures not shown). The former group yield a probability of chance occurrence of 0.199 by the excursion length method and 0.054 by the excursion area method. The latter group yields ≈ 1.000 by both methods. Therefore, the lunar effect is present at a level not too far from the significant 5% during disturbed times if the moon is close to the ecliptic plane at full moon. Apparently, the negative effects of disturbed times are much less influential than the positive effects of low latitude in establishing the lunar mechanism.

2. *Lunar parallax at full moon.* (a) There is approximately a 13% variation in moon-earth distance. The moon's equatorial horizontal parallax varies from about 53' to 62'. To investigate the influence of the moon-earth distance on the lunar modulation mechanism, the 383 lunar periods are separated into two groups. The calculation for the close-to-earth half with lunar parallax greater than 58' is shown in Figure 7, and the far-from-earth half with lunar parallax less than 58' is shown in Figure 8. The lunar modulation seems to be effective in both groups, although the close-to-earth group seems to show the lunar influence

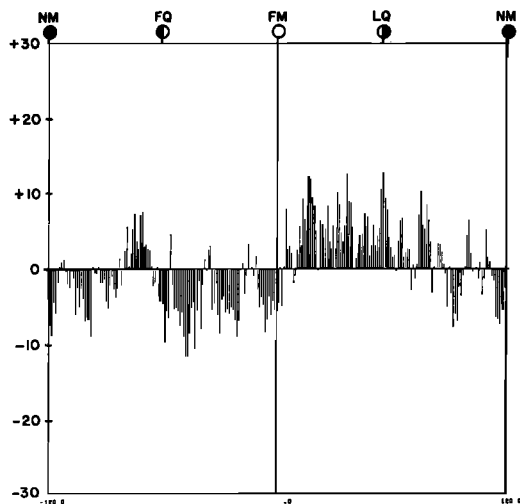


Fig. 7. Same as Figure 1 (half data with lunar parallax at full moon greater than 58').

somewhat more clearly. A comparison of Figures 7 and 8 with Figures 1 and 2, however, suggests that the lunar latitude might be a much more important influence than the moon-earth distance on the modulation mechanism.

(b) The lunar periods of small \bar{K}_p are divided into a near group consisting of 96 cases with parallax range 58' to 62', and a distant group consisting of 96 cases with parallax range 53' to 58'. The per cent departure analyses are shown in Figures 9 and 10, respectively. Here again the lunar effect is somewhat evident in both groups but at a similar level of significance.

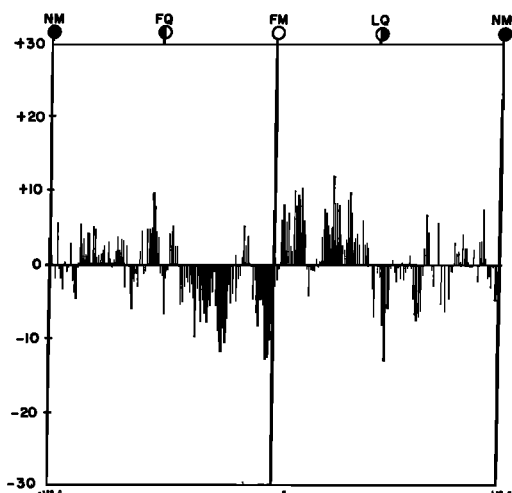


Fig. 8. Same as Figure 1 (half data with lunar parallax at full moon less than 58').

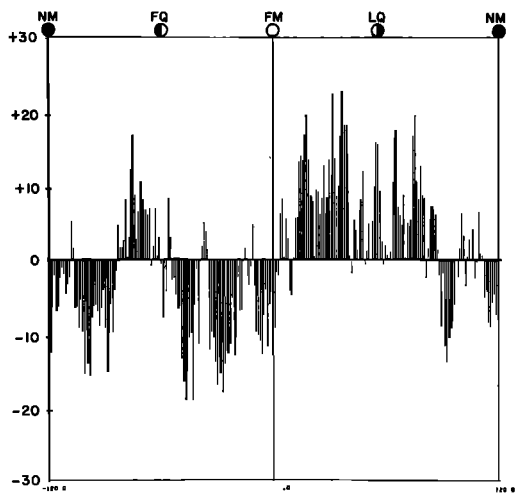


Fig. 9. Same as Figure 1 (quarter data with small \bar{K}_p and lunar parallax at full moon greater than 58').

(c) Since we have shown previously that the epochs within 3.5° of the ecliptic plane show a clear lunar effect, we now separate this group into a close-to-earth group (95 cases) of parallax greater than 58' and a far-from-earth group (96 cases) of parallax less than 58'. They are shown in Figures 11 and 12, respectively. Both groups show the lunar influence at a similar level of significance.

(d) The determination of the probabilities of chance occurrence of the results of the lunar

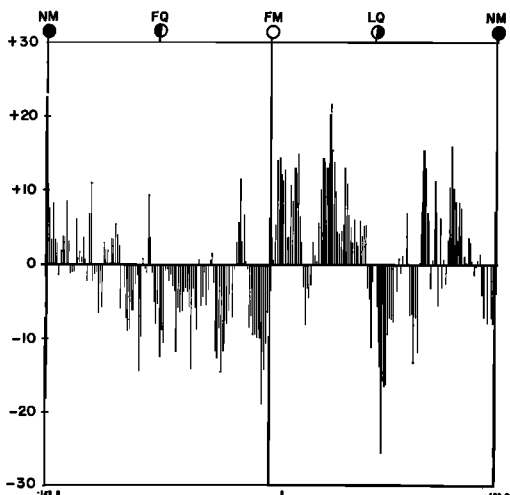


Fig. 10. Same as Figure 1 (quarter data with small \bar{K}_p and lunar parallax at full moon less than 58').

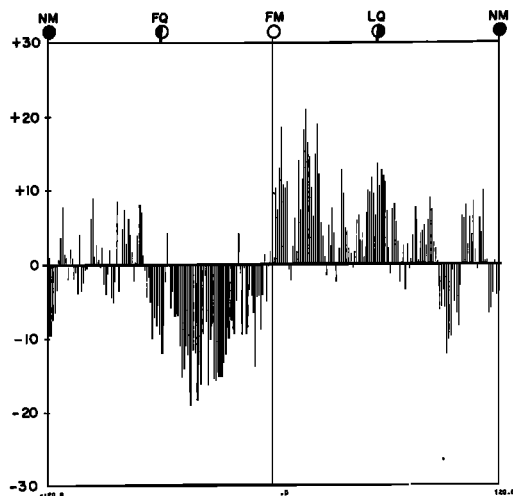


Fig. 11. Same as Figure 1 (quarter data with lunar latitude less than 3.5° and lunar parallax greater than $58'$).

parallax investigations are listed in Table 2.

Speculation on suggested physical mechanisms. A physical mechanism for the explanation of the lunar modulation of geomagnetic activity must be sought either within the sphere of tidal effects or geomagnetic tail interactions. Satellite measurements of magnetic fields and particle fluxes, as well as theoretical studies of the geomagnetic tail, can be expected to contribute to our understanding of the problem.

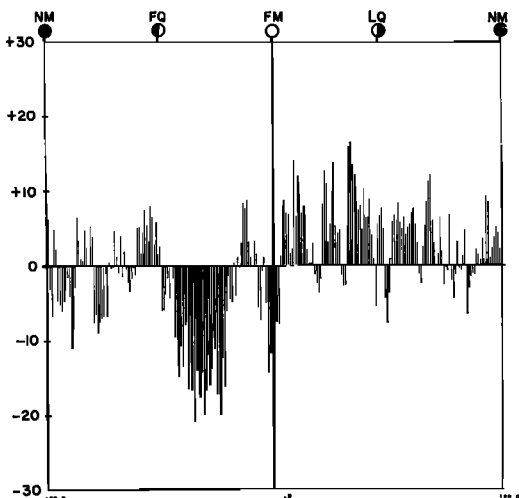


Fig. 12. Same as Figure 1 (quarter data with lunar latitude less than 3.5° and lunar parallax less than $58'$).

TABLE 2. Probability of Chance Occurrence for Lunar Parallax Studies

Lunar Parallax Studies	Excursion Length Method	Excursion Area Method
Fig. 7	0.016	0.016
Fig. 8	0.130	0.214
Fig. 9	0.193	0.311
Fig. 10	0.192	0.497
Fig. 11	0.174	0.029
Fig. 12	0.117	0.016

A simple tidal mechanism presents difficulties: (1) There is no corresponding effect at new moon to match the variations about full moon that have been reported. (2) The tide-generating force varies as M/D^3 , where M is the mass of moon and D its distance from the earth; therefore, a 13% variation in distance should produce approximately a 40% variation in tide-generating force between the extremes at perigee and apogee. The variations to be expected between the close-to-earth and far-from earth groups studied in Figures 7 to 12 would, of course, be considerably less. It is not altogether certain that the cases studied are capable of revealing a variation of the expected magnitude, if such were to exist. However, the figures suggest that any influence of moon-earth distance on the physical mechanism must be extremely small, if it exists at all.

A distant geomagnetic tail extending at least to the moon has been suggested by *Axford* [1962], *Piddington* [1960], and *Dessler* [1964] on theoretical grounds and supported by the Explorer 10 [*Heppner et al.*, 1963], Explorer 14 [*Cahill*, 1964], and Imp 1 [*Ness*, 1965a] measurements. It seems almost certain that the moon finds itself within the magnetosphere in the vicinity of the full-moon position. However, the decrease of geomagnetic activity is present for several days before full moon, and a lunar effect is completely absent for lunar latitudes at full moon greater than 4° . It would seem that the lunar modulation mechanism is anisotropic, having an 'interaction radius' in the vicinity of the plane of the ecliptic that is approximately one order of magnitude larger than perpendicular to the plane.

The first experimental detection of a neutral sheet in the geomagnetic tail was accomplished

by Ness [1965b], and the observation of enhanced fluxes of electrons above 40 kev in the vicinity of the neutral sheet by Frank [1964] and Singer *et al.* [1965]. Petschek [1964] and Axford *et al.* [1965] indicate that the neutral sheet is inherently unstable and bounded by shock waves, wherein magnetic field annihilation provides the energy for acceleration of particles either toward or away from the earth. The neutral sheet is suggested as one possible agency having approximately the proper geometry for conveying the lunar modulation of geomagnetic activity. Associated magnetohydrodynamic effects may be equally important.

A geomagnetic tail-neutral sheet mechanism also presents difficulties: (1) the decrease of geomagnetic activity commences a few days before the moon may be expected to be within the geomagnetic cavity, and (2) owing to the tilt of the moon's orbit, the decrease of geomagnetic activity just before full moon occurs when the moon is at high latitudes seemingly removed from the neutral sheet.

The geomagnetic tail, although apparently a permanent feature of the magnetosphere, will exhibit variations determined by existing solar-wind conditions. A statistical study that combines almost 100 lunar periods cannot hope to see sharply the moon suddenly modulating the flux of particles down the neutral sheet at some point, or disturbing the inherently unstable sheet for some definite period of time. The same lunar phase will invariably meet the geomagnetic cavity at a variety of locations, making it difficult to see clear physical effects in the statistical data. Individual case studies will have to be made, in which magnetic fields and particle fluxes are observed as the moon interacts with the geomagnetic cavity, before the true nature of the lunar modulation of geomagnetic activity can be understood.

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